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THE UNIVERSITY OF MICHIGAN

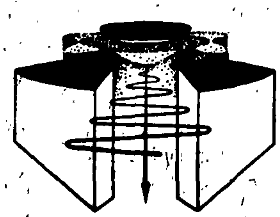
RESEARCH AND DEVELOPMENT ON HIGH-POWER CRESTATRONS FOR THE 100-300 MC FREQUENCY RANGE

QUARTERLY PROGRESS REPORT NO. 12

Period Covering April 1, 1963 to July 1, 1963

ELECTRON PHYSICS LABORATORY

Department of Electrical Engineering



By: G. T. Konrad

Approved by: J. E. Rowe

July, 1963

CONTRACT WITH:

NAVY DEPARTMENT BUREAU OF SHIPS, ELECTRONICS DIVISION, CONTRACT NO. NObsr-81403, PROJECT SERIAL NO. SF0100 201, TASK 9294.

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THE UNIVERSITY OF MICHIGAN
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RESEARCH AND DEVELOPMENT ON HIGH-POWER CRESTATRONS

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This report covers the period April 1, 1963 to July 1, 1963

Electron Physics Laboratory
Department of Electrical Engineering

By: G. T. Konrad.

Approved by: J. E. Rowe.
J. E. Rowe, Director
Electron Physics Laboratory

Project 03783

NAVY DEPARTMENT BUREAU OF SHIPS
ELECTRONICS DIVISION
CONTRACT NO. NObsr-81403
PROJECT SERIAL NO. SF0100 201
TASK NO. 9294

July, 1963

ABSTRACT

The $P_\mu = 20$ hollow beam gun has been programmed for solution on a digital computer. The electron trajectory plots obtained are described. The necessary steps to be taken in order to improve the gun performance are listed.

A number of 100-watt Crestatrons have been tested. Even though the saturation power output is still somewhat low, it is shown that the bandwidth as well as the conversion efficiency are satisfactory. The results of tapering the phase velocity of the slow-wave structure are described. A suggestion is made on how to take advantage of phase focusing near the tube output more fully.

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PERSONNEL

Scientific and Engineering Personnel		Time Worked in Man Months*
J. Rowe	Professor of Electrical Engineering	.11
R. Lomax	Assistant Professor of Electrical Engineering	.33
J. Boers	Associate Research Engineers	1.16
G. Konrad		.65
W. Rensel	Assistant Research Engineer	.37
A. Collins	Research Assistants	.25
J. Loh		.25
J. Mason		.11
C. Rhee		1.90
Service Personnel		7.33

* Time Worked is based on 172 hours per month.

QUARTERLY PROGRESS REPORT NO. 12

FOR

RESEARCH AND DEVELOPMENT ON HIGH-POWER CRESTATRONS

FOR THE 100-300 MC FREQUENCY RANGE

1. Introduction

Contract NObsr-81403 comprises a research and development program on high-power 100-300 mc Crestatrons. The aim is to construct compact 100-watt Crestatrons employing permanent magnet focusing. Initially the tubes will be tested in a solenoid until they meet electrical specifications. Ultimately the permanent magnet focused tubes employing a depressed potential collector will be ruggedized so as to meet environmental specifications. This work is being conducted by the Bendix Research Laboratories on a subcontract from The University of Michigan.

Theoretical as well as experimental studies on high-perveance hollow-beam electron guns, in addition to electrostatic focusing systems initiated some time ago on this program, are being continued by The University of Michigan. The ultimate goal of these studies is to demonstrate the feasibility of using electrostatically focused, high-power, hollow electron beams in microwave devices. In addition it is intended to work out a design for an electron gun compatible with a high-power vhf Crestatron.

2. Hollow-Beam Gun Work

During the past quarter work was done on the scaled $P_\mu = 20$ gun. It will be recalled that this gun was scaled from the $P_\mu = 4.46$ model used in the electrostatically focused Crestatron. The work consisted of some digital computer program modifications and several trajectory calculations.

The program modifications were mainly simplifications in the required input data in order to reduce the computing time. The initial trajectory calculations indicate that the electron beam is too divergent in the gun region due to space-charge effects. Modifications in the gun electrodes are now under consideration in order to correct for the stronger space-charge forces in this more dense electron beam. It will also be necessary to change the anode geometry somewhat due to the undesirable effect of the large anode hole on the potential distribution at the cathode. All these changes are presently being incorporated into the digital computer program. The new trajectory runs will be obtained early during the coming quarter.

The vhf electrostatically focused Crestatron has been dismanteled so that the original $P_\mu = 4.46$ gun can be removed and modified in accordance with recent beam analyzer results described in previous progress reports. It is intended to obtain beam transmission data and power output curves for the tube in the presence of r-f drive. This will permit evaluation of the electrostatic focusing system in the Crestatron. These tests will also be conducted during the coming quarter.

3. Work Conducted at the Bendix Research Laboratories*

3.1 Introduction. In the following the status of the tube program is reviewed and the component parts of the tubes including the matching sections and the circuits are described.

This description is included so that the reader may better evaluate the experimental data which will be presented later in the report. A brief representation of the results of the first two operable metal-ceramic tubes is also included; then the results of succeeding tubes that have been

* This material was submitted by Dr. J. G. Meeker of the Bendix Research Laboratories.

r-f tested to date are presented. The tubes tested thus far have not achieved full power output for reasons noted in the later sections of this report. However, the data are encouraging since they show that the tubes possess excellent bandwidth properties and satisfactory efficiencies. Conclusions are drawn and recommendations set forth for Task II. These recommendations describe modifications that must be made in the tubes to achieve the full power output. Work is already progressing along these recommended lines.

3.2 General Description of Metal-Ceramic Tubes. As shown in Fig. 3.1, these tubes have a helical circuit which is mounted on three precision-ground ceramic rods. These rods hold the circuit concentric within a shield envelope having an inside diameter 1.5 times that of the helix mean diameter. Matching sections at each end of the tube serve the function of tapering the shield gradually toward the helix. This causes the helix to appear as a line above ground plane with a spacing which changes gradually with distance; thus the impedance of the transmission line is tapered gradually to effect a good match on and off the high impedance helical circuit.

The collector and the electron gun are assembled to the main body of the tube by radial weld flanges. These flanges allow either the collector or the electron gun to be removed from the tube, modifications or repairs to be made, and to be assembled with the tube again for further testing. The electron gun is a self-contained unit which is completely assembled before being put into the tube. Figure 3.2 shows the details of electron gun construction.

Three different models of the r-f matching sections have been used. The first matching sections were 4 inches long and designed for use with a helix circuit of 9.6 inches long. The first tubes tested exhibited more

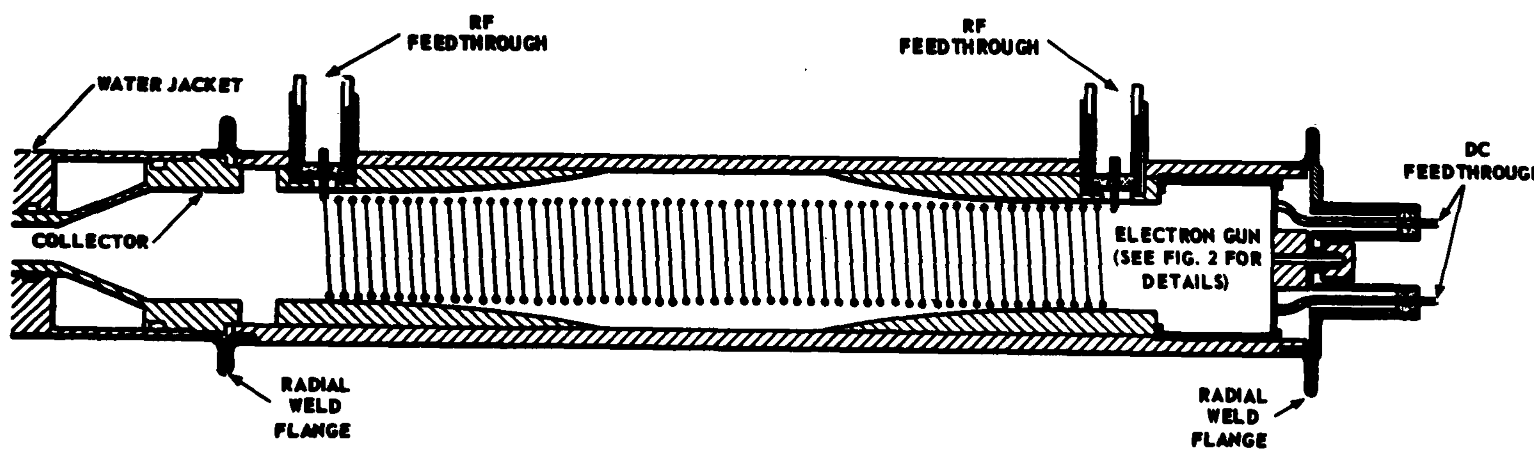

FIG. 3.1 ASSEMBLY DRAWING OF TUBE--DETAILS OMITTED.

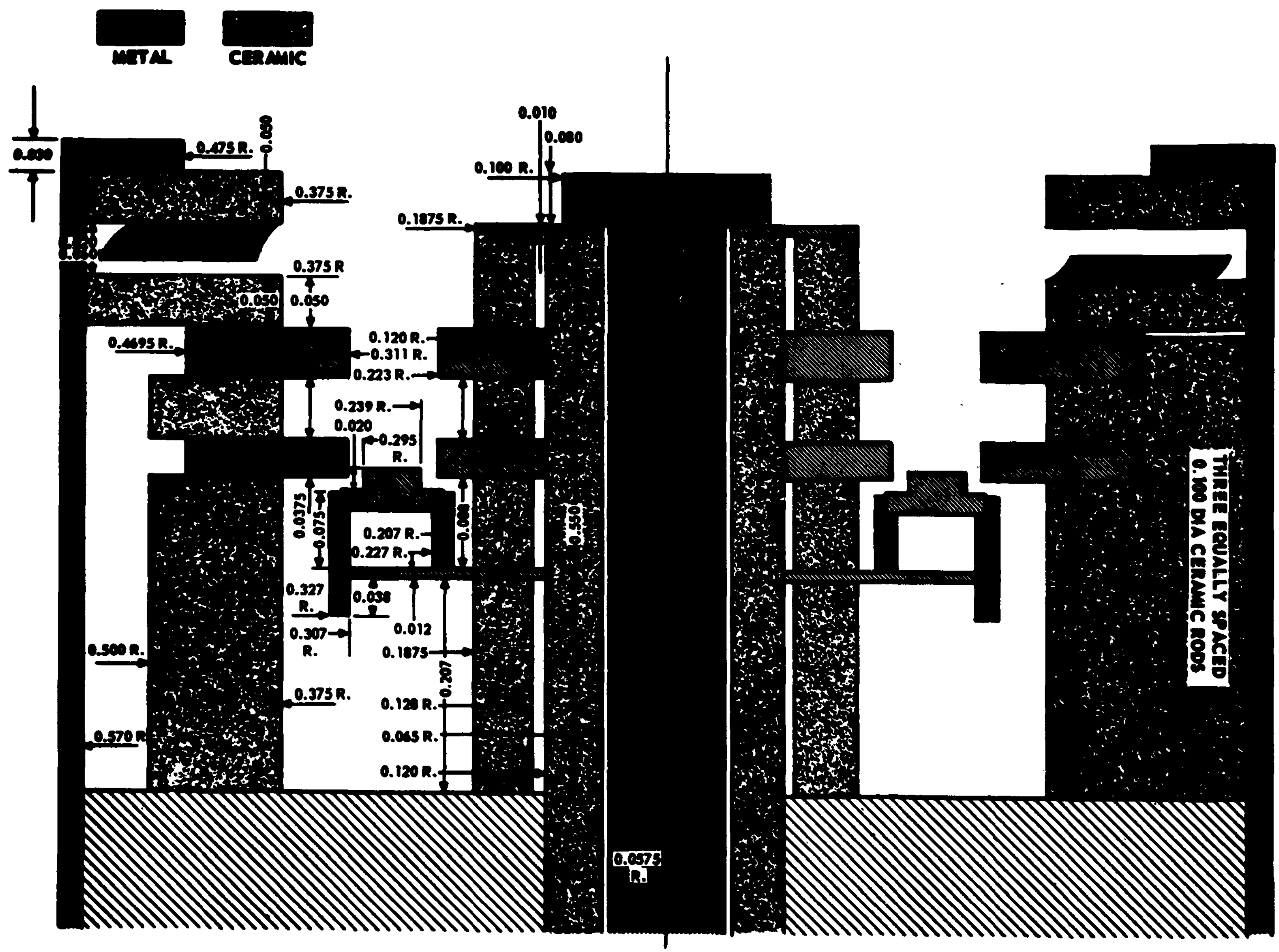

FIG. 3.2 DETAILED ASSEMBLY DRAWING OF GUN.

gain than required; therefore succeeding tubes were shortened and new shorter matching sections were designed. These matching sections were 2 inches in length, but did not provide as good a match as the longer sections. A modification of the long sections was then undertaken in which the two matching sections actually met at the center of the tube. With this arrangement, the r-f matching sections extended over the full length of the circuit helix.

The first tube tested contained a helix of 11.5 TPI. But when r-f testing of this tube indicated that the operating voltage was lower than that desired, helices of 10 TPI were used in succeeding tubes. The 10-TPI helix, however, did not give conversion efficiencies as high as desired.

It has been shown previously[1] that the efficiency of a traveling-wave tube may be improved by reducing the phase velocity of the circuit near the output end. In O-type traveling-wave tube operation, kinetic energy of the electron beam is transferred, via the interaction process, to r-f energy flowing on the circuit. As this transfer of energy takes place, the electrons must necessarily slow down. The electron bunches in the beam are first formed in the optimum phase position of the wave on the circuit resulting in a slowing of the bunched electrons. As the electrons slow down they start to slip back in phase. When this slippage becomes great enough, which is when the output power of the tube is becoming an appreciable portion of the d-c drift energy of the electron beam, the bunches can fall back into an accelerating phase of the wave. At this point, the tube has reached saturation and maximum efficiency has been obtained. However, if the phase velocity on the circuit is

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1. Meeker, J. G., "Phase Focusing in Linear Beam Devices", Tech. Report No. 49, Electron Physics Laboratory, The University of Michigan; August, 1961.

slowed down so that the wave and electron bunches maintain a constant phase relation, then the maximum transfer of energy from the beam to the circuit is increased, i.e., the electrons may be slowed to a smaller percentage of their initial drift velocity before falling out of step with the wave. To improve the efficiency of the circuits in the tubes, the last three tubes reported on contained tapered circuits.

3.3 Experimental Data. Of eight tubes started in assembly, seven were completed and five were r-f tested. Table 3.1 lists the more important physical and d-c electrical parameters of these tubes.

Traveling-wave tube No.1 had a helix of 11.5 TPI, was 9.6 inches long, and used 4-inch matching sections at each end. The rated beam current for this tube is 452 milliamperes, but due to electrical problems in the electron gun, the tube was tested only to 105 milliamperes of beam current.

A concise picture of the operation of a tube can be gained from a basic output versus input plot such as that of Fig. 3.3 for tube No. 1. Several pieces of information can be ascertained. It is seen that tube No. 1 will operate at less than 1/4 rated current with excellent gain and bandwidth, although not extending down to 100 megacycles as originally desired. The operating voltage was also lower than anticipated. At this point it was decided to discontinue assembly work on tube No. 2 (physically identical to tube No.1) and to go ahead with tube No. 3 which would contain a 10 TPI helix to effectively increase the voltage of operation and decrease the electrical length, thereby decreasing the small-signal gain.

Figure 3.4 shows the power output versus power input plot for tube No. 3. One can see that the small-signal gain was decreased and the band of operation is more nearly that desired. The operating voltage was

TABLE 3.1

PHYSICAL AND ELECTRICAL PARAMETERS OF TUBES TESTED

TUBE NUMBER	PHYSICAL								ELECTRICAL							SPECIAL NOTES
	OVERALL LENGTH	HELIX LENGTH	HELIX MEAN DIA. (IN.)	HELIX TPI	HELIX WIRE SIZE	TYPE R.F. CONNECTORS	MATCHING SECTIONS		GUN TYPE	BEAM DIA. INCHES		RATED COLLECTOR CURRENT	RATED VOLTAGE	OPERATING CONDITIONS		
							TYPE	LENGTH EACH END		INNER	OUTER			BEAM CURRENT	BEAM VOLTAGE	
TWT-143-A-1	16	9.6	0.726	11.5	0.030	COAX DIRECT PIN. CONN.	TAPERED OUTER SHIELD	4"	HOLLOW BEAM	0.470	0.590	452	870	185	600	GLASS TO KOVAR RF FEEDTHROUGHS AND STEM HEADER
TWT-143-A-2	16	9.6	0.726	11.5	0.030	COAX DIRECT PIN CONN.	TAPERED OUTER SHIELD	4"	HOLLOW BEAM	0.470	0.590	452	870	---	---	TUBE NOT COMPLETED DUE TO DATA ON TWT-143-A-1 INDICATING CHANGE OF PLANS
TWT-143-A-3	16	9.6	0.726	10	0.030	COAX DIRECT PIN CONN.	TAPERED OUTER SHIELD	4"	HOLLOW BEAM	0.470	0.590	452	870	143	700	THIS TUBE DEVELOPED AN OPEN INNER ANODE AND ARC BREAKDOWN
TWT-143-A-4	11	5.6	0.726	10	0.030	COAX DIRECT PIN CONN.	TAPERED OUTER SHIELD	2"	HOLLOW BEAM	0.470	0.590	452	870	250 AND 300	600 TO 700 AND 830	ULTIMATE FAILURE DUE TO LEAKAGE IN GUN
TWT-143-A-5	11	5.6	0.726	10	0.030	COAX DIRECT PIN CONN.	TAPERED OUTER SHIELD	2"	HOLLOW BEAM	0.470	0.590	452	870	---	---	HEATER FAILURE BEFORE DATA WAS OBTAINED
TWT-143-A-6	11	5.6	0.726	10 TAPERED TO 20	0.030	COAX DIRECT PIN CONN.	TAPERED OUTER SHIELD	2"	HOLLOW BEAM	0.470	0.590	452	870	---	---	HELIX CONNECTION TO RF FEEDTHROUGH FAILED DURING BAKEOUT
TWT-143-A-7	11	5.6	0.726	10 TAPERED TO 20	0.030	COAX DIRECT PIN CONN.	TAPERED OUTER SHIELD	2.8"	HOLLOW BEAM	0.470	0.590	452	870	250	550 TO 650	HELIX TAPERED TOO MUCH. RF PERFORMANCE WAS POOR
TWT-143-A-8	11	5.6	0.726	10 TAPERED TO 15	0.030	COAX DIRECT PIN CONN.	TAPERED OUTER SHIELD	2"	HOLLOW BEAM	0.470	0.590	452	870	305	820	HELIX TAPERED 1/2 THAT OF TWT-143-A-7 BUT STILL TOO MUCH.

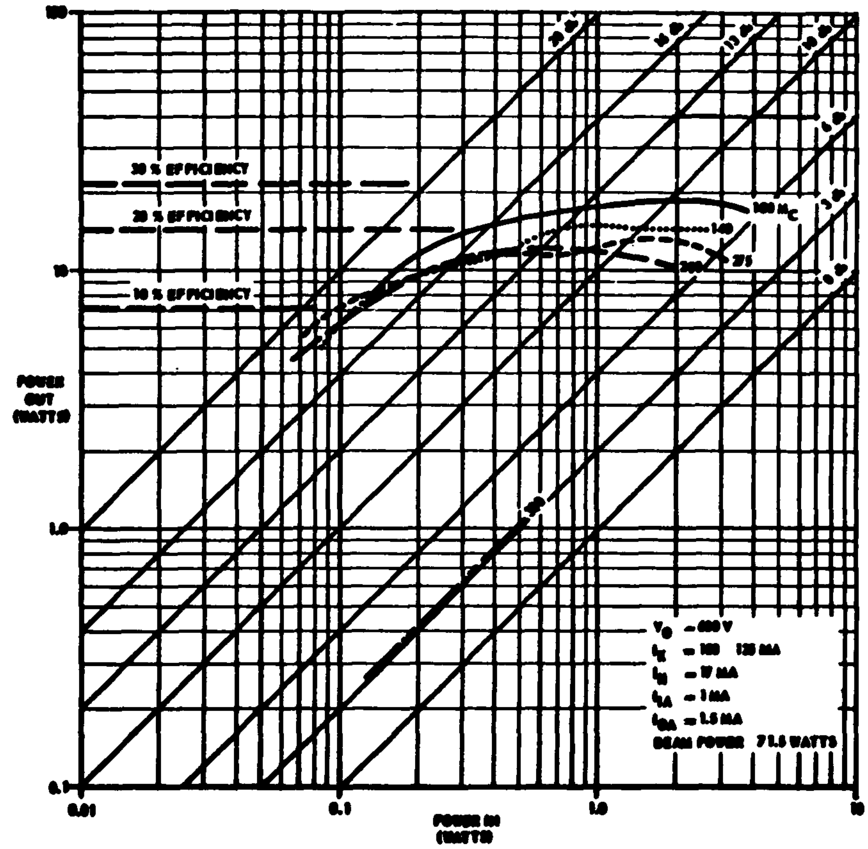

FIG. 3.3 PERFORMANCE CHARACTERISTICS OF TUBE NO. 1.

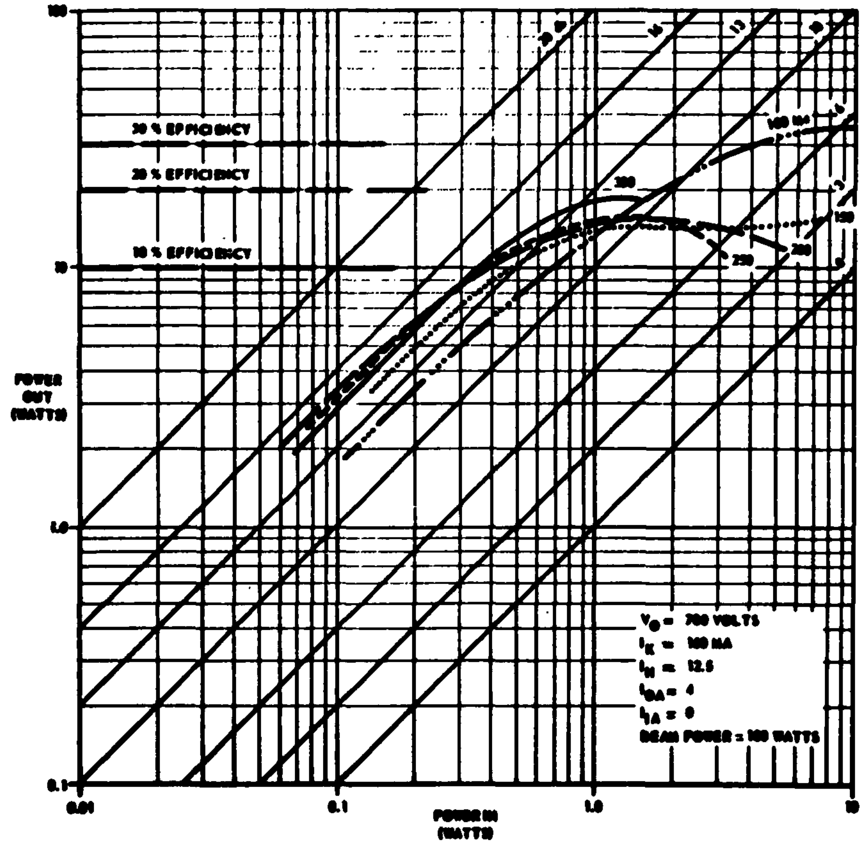

FIG. 3.4 PERFORMANCE CHARACTERISTICS OF TUBE NO. 2.

increased slightly; however, the efficiency decreased and at saturation measured approximately 15 percent. Since this tube had sufficient gain at approximately 1/3 beam current it was decided to shorten future tubes. Thus, succeeding tubes had a 5.6 inch long helix as compared with the 9.6 inch helix of the first three tubes.

In the evaluation of the gain data, it is necessary to account for variations in the r-f matches between tubes. The VSWR of the r-f matches of tube No. 1 are given in Fig. 3.5. Three curves are shown--one is the input match with the output isolated; one the output match with the input isolated; while the last curve is the input with the output end not isolated, but terminated in a 50-ohm load. It is evident that individual matches with a VSWR of less than 2 to 1 were achieved across the band from 100 to 300 megacycles and even above. With a VSWR of 2 to 1 on each end, oscillations due to these mismatches can be expected if the tube were to develop in excess of 19 db of gain. With a less than perfectly matched load, oscillations can be expected with even less gain, and oscillation did in fact occur whenever the gain approached 18 or 19 db in our experiments.

Figure 3.6 gives the same match data for tube No. 3. As can be seen, the matches were even better on this tube than on tube No. 1 and calculations indicate that such matches should allow gains of nearly 27 db before oscillation. This tube did in fact prove to be considerably more stable than the first tube.

Tube No. 4 contained short matching sections; therefore, it was not possible to obtain an r-f match as good as that in tube No. 1 and tube No. 3. Figure 3.7 shows the r-f match for tube No. 4. This figure shows only the double-ended VSWR since it was extremely difficult to obtain isolation

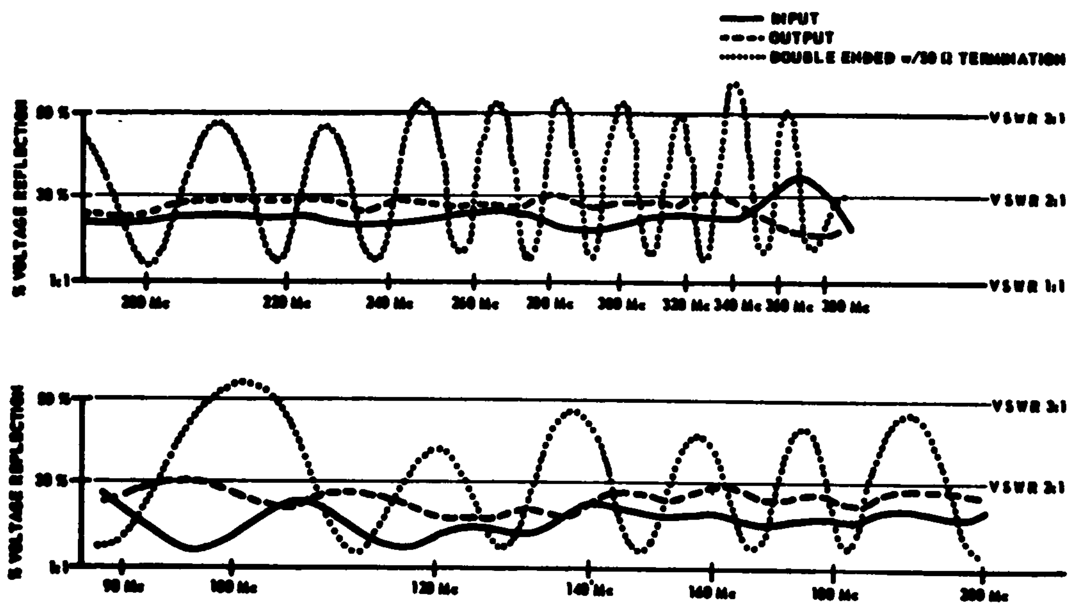

FIG. 3.5 VSWR VS. FREQUENCY FOR TUBE NO. 1.

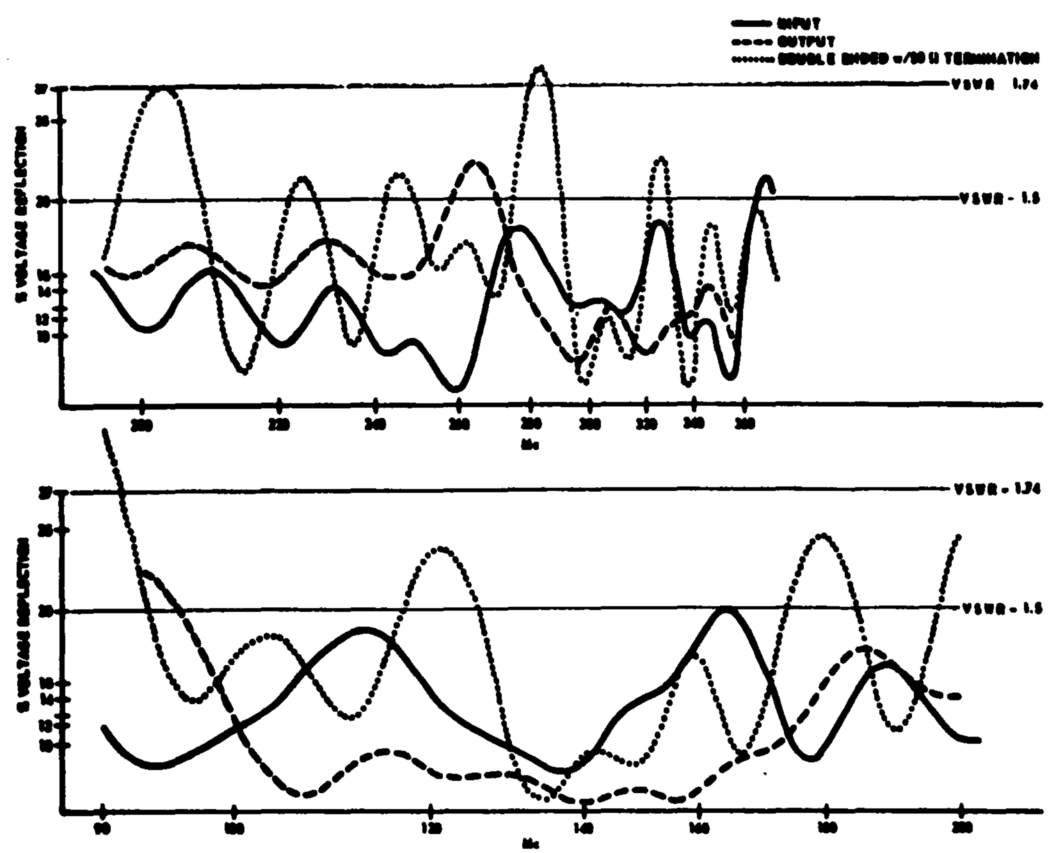

FIG. 3.6 VSWR VS. FREQUENCY FOR TUBE NO. 3.

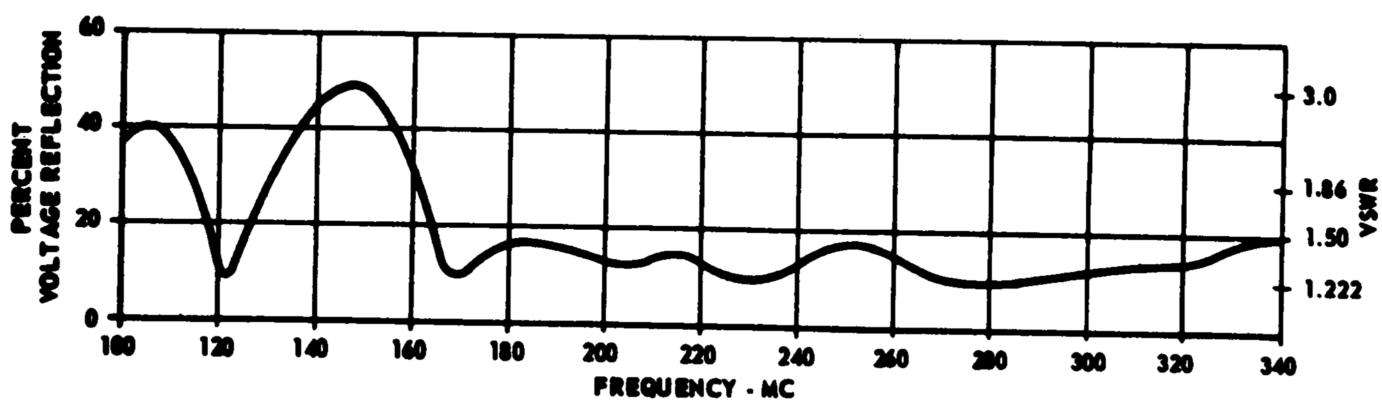

FIG. 3.7 MATCH OF TUBE NO. 4.

between the two ends of the short tube. In the frequency range between 100 and 160 megacycles the VSWR was higher than 2 to 1.

Tube No. 4 was operated as high as 3/4 rated current or approximately 350 milliamperes. Figure 3.8 shows power output versus power input data from 100 to 300 megacycles. It is seen that a maximum of 58 to 60 watts was obtained at the high frequency end of the band. It is also seen that below 200 megacycles, where the match was definitely poorer, gain and power output were also definitely poorer. Because it appeared that the tube would operate well at frequencies above 300 megacycles, it was decided to test the tube as high in frequency as practicable.

In these tests, however, leakage in the electron gun forced use of a decreased beam current. Figure 3.9 shows power output versus power input with the cathode current at 250 milliamperes. The frequency range covered is 400 to 1000 megacycles. It is seen that small-signal gain remained good over this very broad frequency range. Power outputs of 20 to 30 watts were obtained, except for 10 watts at 600 megacycles. The efficiency of this tube ranged from 17 to 22 percent. Optimum operating voltage varied between 750 and 850 volts, depending primarily on the beam current.

Tube No. 5 had a heater failure soon after bake-out and before r-f data could be taken. Tube No. 6 had a helix connection fail during bake-out so that no r-f data could be taken. Because these two tubes were not of a demountable design, repairs were nearly impossible. Therefore both tubes were set aside and efforts were directed on tube No. 7.

Figure 3.10 shows the match data for tube No. 7 which incorporated a 10 TPI helix tapered to 20 TPI near the output end. The r-f test data in Fig. 3.11 shows that this amount of taper was too much for optimum

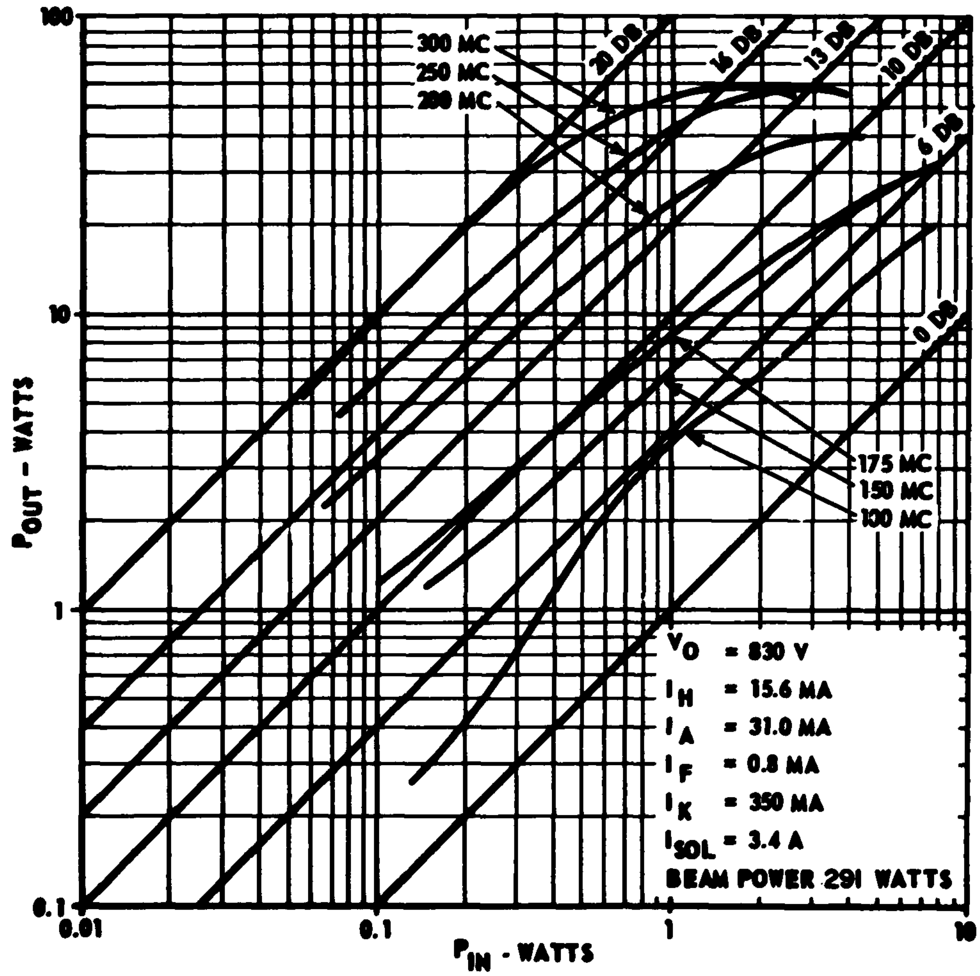

FIG. 3.8 POWER OUT OF TUBE NO. 4. (100-200 mc)

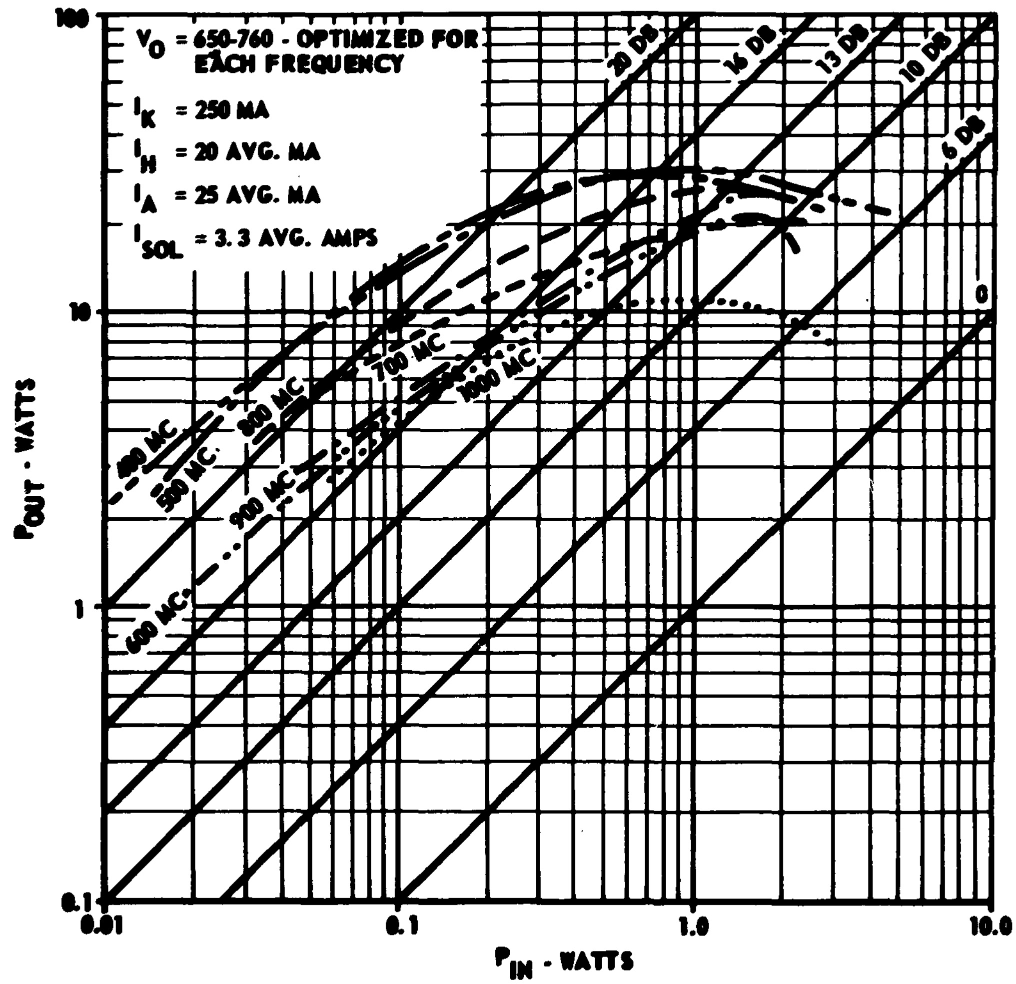

FIG. 3.9 POWER OUT OF TUBE NO. 4. (400-1000 mc)

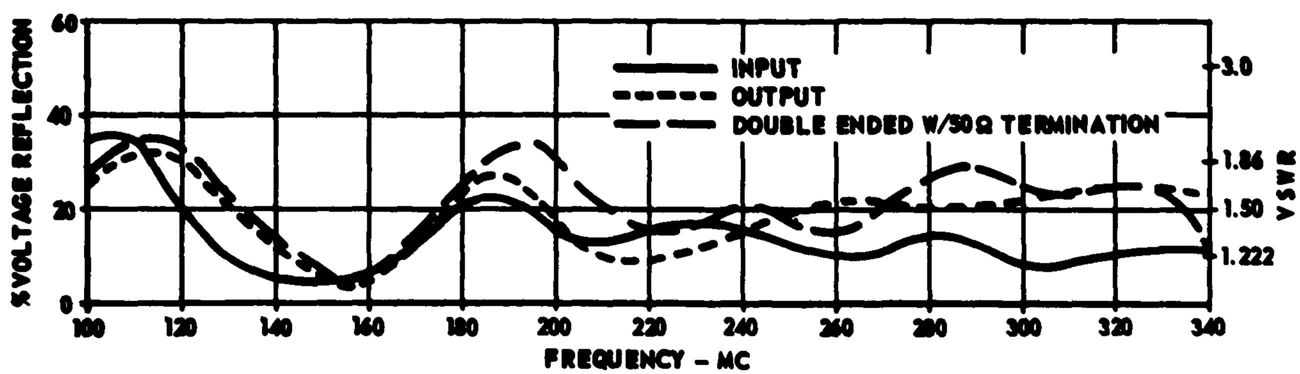

FIG. 3.10 MATCH OF TUBE NO. 7.

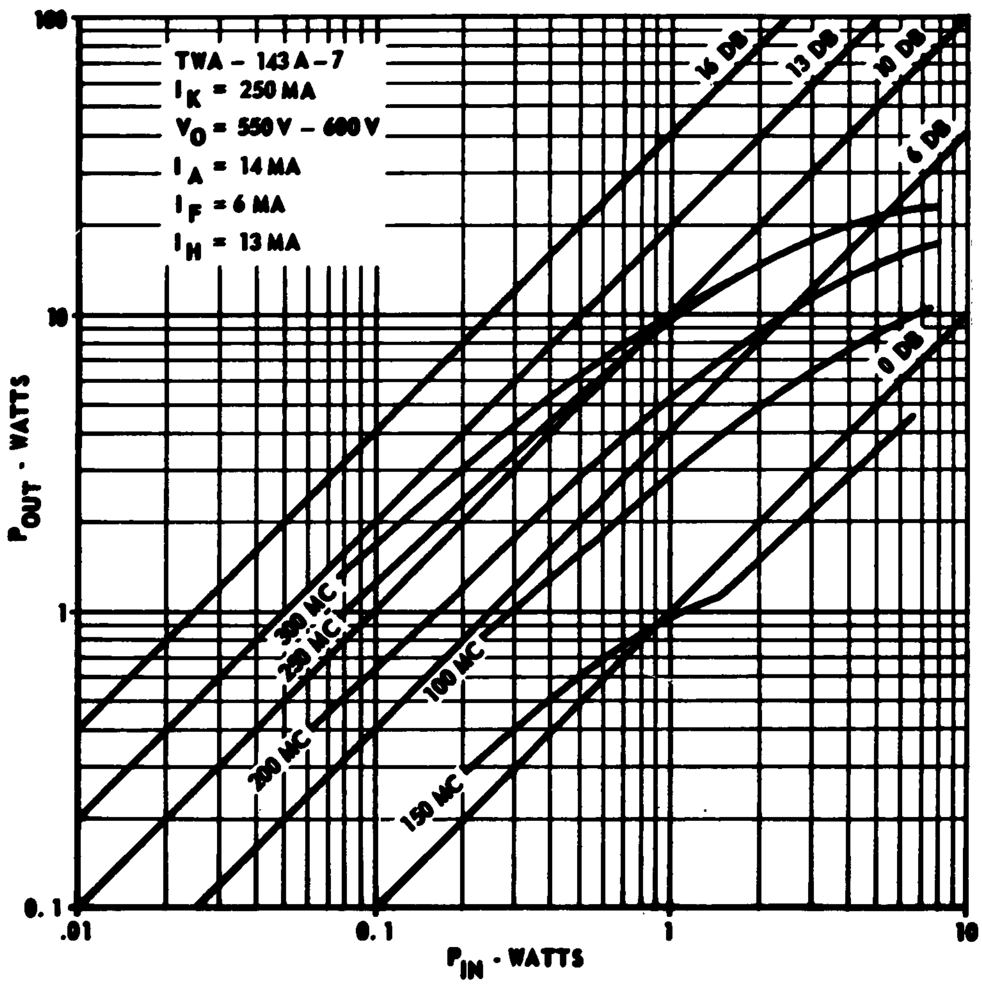

FIG. 3.11 POWER OUT OF TUBE NO. 7.

performance; small-signal gain, power output and efficiency were all detrimentally affected. The operating voltage was also reduced to approximately 575 volts as compared to 800 volts for tube No. 4.

Tube No. 8 contained a helix which tapered from 10 to 15 TPI near the output end. The match data on tube No. 8 is given in Fig. 3.12 and r-f test data in Fig. 3.13. A comparison of Fig. 3.13 with Figs. 3.11 and 3.8 shows that the helix tapered to 15 TPI operated better than the one tapered to 20 although not as well as the uniform 10-TPI helix.

3.4 Evaluation of Experimental Data. It is apparent that tapering the circuits of these tubes has not improved the r-f interaction efficiency. A new analysis of the r-f matching sections reveals the difficulty. Consideration of conventional means of coupling to and from helical structures, including the pin matches used in these tubes with the tapered shields shows that in the output matching section the interaction impedance, i.e., the strength with which the beam and circuit r-f wave interact, is adversely affected. Greater conversion efficiency could be expected with increased interaction impedance at the output region of the helix. It therefore appears desirable to modify the r-f matching so that the increased interaction impedance may be realized. In a pin match this may be accomplished by transforming the transmission-line impedance at a point away from the interaction region and connecting to the helix with a high impedance line, thus requiring no matching over any of the interaction region. The effect of this change would be to improve efficiency and increase the gain of the tube. R-f matching tests are now in progress to effect this modification.

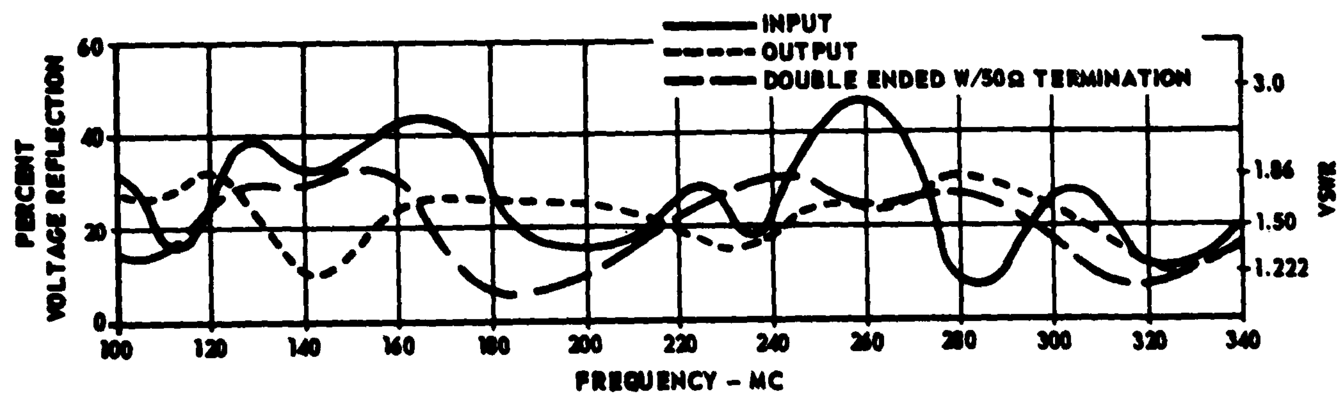

FIG. 3.12 MATCH OF TUBE NO. 8.

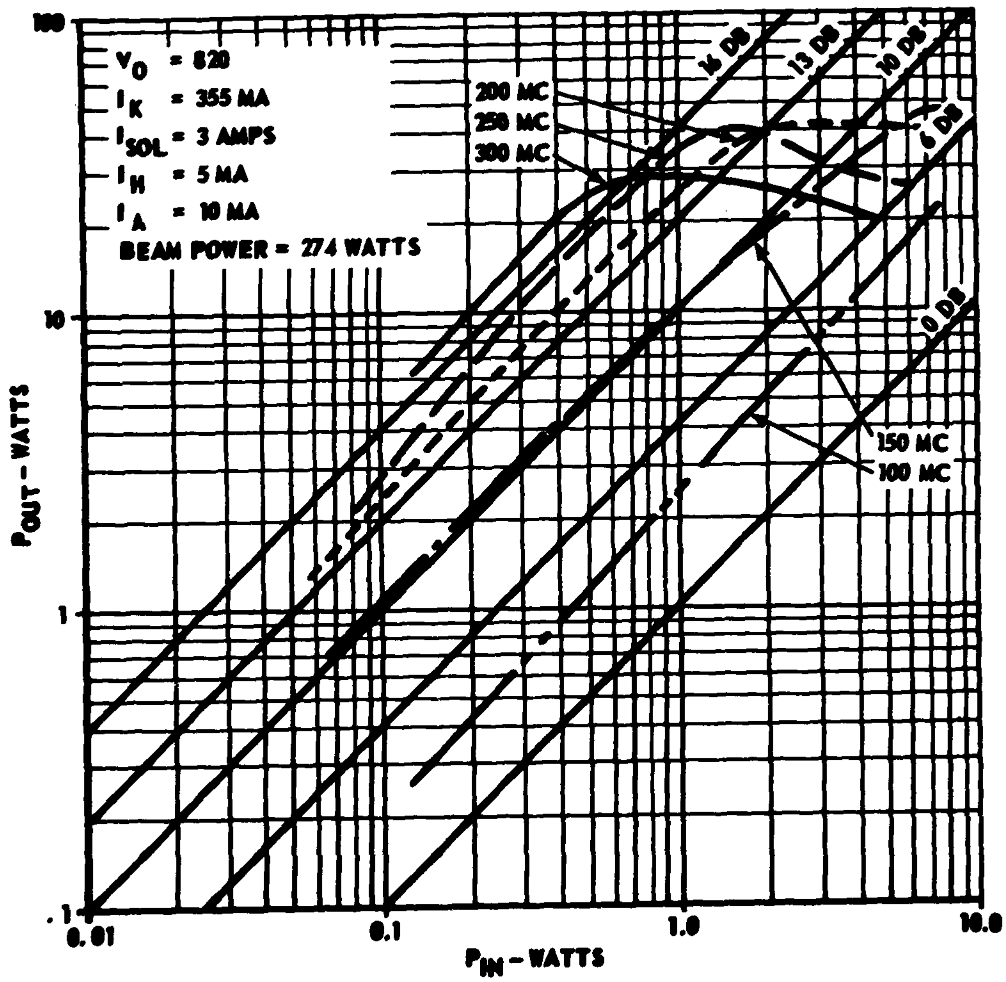

FIG. 3.13 POWER OUT OF TUBE NO. 8.

The literature[2] shows that as the shield around the helix is moved closer to the helix, the phase velocity is reduced. R-f tests indicate that the drastic shielding of the r-f match section in these tubes has produced considerable slowing of the wave. When it is remembered that this slowing process is taking place at the output end of the helix it becomes apparent that phase velocity tapering was incorporated in tube No. 4 even though no TPI tapering of the helix was used. The reasons for the failure of the tapered circuit are now apparent with the phase velocity tapering due to the shield and the decreased interaction impedance.

Isolation of the r-f matching sections from the r-f interaction region will improve tube operation in two respects:

1. The phase velocity tapering will be more controllable, and
2. The interaction impedance will be maintained to the end of the interaction region.

The tubes to date have produced a maximum power output of 60 watts with maximum efficiencies ranging from 17 to 22 percent. Calculations indicate that the traveling-wave tube gain parameter C is reduced to approximately one-half the uniform helix value when the shield closely approaches the helix. It is expected that, with a high C maintained to the end of the interaction region, the interaction efficiency will be considerably increased. The electron gun has not yet operated to full beam current, and 60 watts were obtained with 350 milliamperes in the beam. It is anticipated that the correction of the problem in the electron gun and

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2. Mathers, G. W. C., Kino, G. S., "Some Properties of a Sheath Helix with a Center Conductor or External Shield", Tech. Report No. 65, Electronics Research Laboratory, Stanford University; June, 1953.

the isolation of the r-f matching section from the r-f interaction region will allow the electrical specifications of this tube to be met.

3.5 Conclusions.

a. The small-signal bandwidth, though not centered in the exact frequency range desired, is very wide with tube No. 4 operating from 200 to 1000 megacycles. Due to time limitations, the other tubes have not been tested over the higher frequency ranges.

b. The saturation bandwidth is as wide as the small-signal bandwidth.

c. Because gain has been consistently high, the 5.6-inch helix length is believed to be adequate.

d. The matches affect the stability of the tube to a high degree and very good matches are required. The tube will require either a well-matched load or isolators between the tube and load.

e. The r-f matches adversely affect the interaction impedance. It is planned to isolate at least the output r-f matching section from the interaction region for improved efficiency.

f. The gradually tapered shield r-f match has affected the phase velocity of the helix, yielding phase velocity tapering at each end of the helix. It is particularly desirable to eliminate this effect at the output end of the helix. It will be removed from the interaction region by isolation of the r-f matching section (as necessitated because of the interaction impedance problem). A controlled amount of phase velocity tapering can then be re-introduced with the tapered helix.

4. Summary and Future Work

During the coming quarter the digital computer work initiated on the scaled $P_\mu = 20$ gun will be completed. The electron gun presently used in the magnetically focused Crestatrons will also be programmed for

the computer and electron trajectories will be obtained. This will help certain refinements to be made in order to obtain improved beam transmission.

Further tests on the electrostatic focusing system will be conducted. The results promise to be significant because a considerably improved gun is now available.

Several more 100-watt Crestatrons will be built and tested in order to ascertain the optimum operating conditions. More work, both theoretical and experimental, needs to be done on the r-f match isolation problem before a suitable transducer can be incorporated in an operable tube. This work appears to be of prime importance in meeting the electrical objectives of the program. After isolation of the matching section, a re-evaluation of the tapered circuit will be undertaken.

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The P_μ = 20 hollow beam gun has been programmed for solution on a digital computer. The electron trajectory plots obtained are described. The necessary steps to be taken in order to improve the gun performance are listed.

A number of 100-watt Crestatrons have been tested. Even though the saturation power output is still somewhat low, it is shown that the bandwidth as well as the conversion efficiency are satisfactory. The results of tapering the phase velocity of the slow-wave structure are described. A suggestion is made on how to take advantage of phase focusing near the tube output more fully.

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